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CERTIFICATE OF ADVANCED STUDIES

EXPLORATION & DEVELOPMENT OF DEEP GEOTHERMAL SYSTEMS

CAS DEEGEOSYS

Geothermal potential evaluation for the northern Chile and strategic energy planning

Dr. Monia Procesi

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INTRODUCTION

Chile is a republic located in South America bordering on the Andes Mountain and Pacific Ocean. The country is sectioned into 15 administrative regions.

Chile is rich in natural resources such as copper, timber, nitrates, precious metals and molybdenum. It is the world's largest producer and exporter of copper; mining is a major industry and an essential part to the Chilean economy. Even though Chile has an abundance of copper and mining resources, it has limited indigenous fossil fuels, indeed over 90% of the fossil fuels need to be imported [1].

Nowadays, the energy demand of Chile is about 57,000 GWh and it is projected to increase from 6 to 7% annually, by 2020 [2]. The installed capacity for electric generation is 16,970 MWe, producing approximately 61,000 GWh/Y. The 63% of the total installed capacity corresponds to fossil fueled power plants, 34% to hydropower plants and only 3% to renewable resources [2]. The main part of the total electricity is consumed by mining and industry sectors.

The electricity market in Chile comprises of two main independent systems:

SING - Northern Interconnected Power Grid;

SIC - Central Interconnected Power Grid

SING has an installed capacity of 4344 MWe and about 99% of which generated by imported fossil fuel. SIC has an installed capacity of 12,490 MWe, over 50% by hydroelectricity and the remaining by fossil fuels [1-2].

Currently the main Chilean energy source is the hydropower. Other renewable resources as wind, solar, biomass and geothermal are poorly developed, but several corporations, as the Centre for Renewable Energy (CER), have been working to ensure optimal participation of renewable energies in the energy matrix of Chile to contribute to the sustainable development of the country [3].

In 2011, The Global Energy Network Institute (GENI) suggested that a strategic energy plan for Chile is necessary in order to ensure the transitions from thermal power plants to renewable energy power plants [3]. This transitions are necessary both to reduce the amount of greenhouse gases into atmosphere and to take off the dependence of imported fossil fuels.

Under such circumstances, renewable energy resources in Chile should become more relevant. The geothermal energy, is not yet exploited here, but among the renewables, has the biggest development potentiality. Although no geothermal power plants have been installed to date, a vigorous geothermal exploration program is under way [4]. Preliminary evaluation of the northern Chile potential ranges from 400 MWe to 1,000 MWe, whereas for the Central-southern part the estimation is between 600 MWe to 950 MWe [1]. This makes Chile one of the most attractive countries for the geothermal energy utilization.
The aim of the work is the evaluation of the geothermal potential in northern Chile in terms of power generation, developing a new strategic energy plan applicable by the northern Interconnected Power Grid (SING). The northern Chile has been chosen for the analysis because more data are available than Central and Southern, and due to the huge energy reliance on imported fossil fuels.

1.1 Description of the subject

In Chile, there are more than 300 geothermal areas located along the Andes, in the extreme north and central-southern part, and associated with Quaternary volcanism. At the present, detailed exploration is being carried out by the state-owned oil company (ENAP), as well as private companies [1]. During the ‘60s and ‘70s detailed geological, geochemical and geophysical survey were carried out in several geothermal systems located in the north of the Country, as well as Surire, Puchuldiza, Lirima, Irruputunco-Olca, Apacheta and El Tatio. Instead, preliminary reconnaissance survey have been done in the central and Southern Chile. These investigation permitted, during the ‘80s, a preliminary evaluation of the geothermal potential of the Country, estimated in 16,000MW for at least 50 years, from geothermal fluids with temperatures exceeding 150°C and located at a depth less than 3000 m [5]. A new evaluation of the geothermal potential of the Northern Chile would be proposed, taking into account the acquisition of new knowledge in terms of geological data and technologies.

Figure 1: Geothermal areas of the Northern Chile. The red box shows the studied area.

1. Regional Setting

The northern Chile has a relatively homogeneous geological setting, consisting of Lower Miocene–Pleistocene ignimbrite deposits and andesitic–rhyolitic volcanic products overlying Middle Cretaceous–Upper Miocene volcano-sedimentary formations [6-11]. The latter, hosts the main hydrothermal reservoirs that are dominantly consisting of andesitic lava and pyroclastic flows, conglomerates, breccias, sandstones, siltstones, limestones, marls and evaporites [8; 12]. Evaporitic surficial deposits, locally named “salares” and composed of borates, subordinate sulfates, carbonates and chlorides, are locally present.

The main hydrothermal systems are located within NS-, NW-trending grabens [7, 8, 13] in the western side of the Pliocene–Holocene Central Andean Volcanic Zone (CAVZ).
For each studied systems, a brief geographical/geological setting with relative descriptions of the geothermal manifestations at surface is reported.

Surire

The Surire hydrothermal system is located at an altitude of 4000–4300 m a.s.l. In 1972, as many as 133 thermal discharges occurred in an area of about 15 km^2 [13]. Presently, most of the bubbling pools and thermal springs of this system are located along the southern border of the salar.

Puchuldiza

The Puchuldiza-Tuja hydrothermal system is located at an altitude of about 4100–4200 m a.s.l., 27 km SW of the active Isluga volcano characterized by permanent fumarolic activity [14]. The fluid discharges within this area are controlled by the Churicollo, Puchuldiza and Tuja faults. Several thermal springs with low gas emission surround the main emission areas [15].

Apacheta

Apacheta is located 105 km NE of Calama City and 55 kmNW of the El Tatio hydrothermal system. A 180 m deep well (PAE-1) drilled by the Chilean National Mining Company (CODELCO) in 1998 produced steam measured at 88 °C [16]. Fluid discharges emitting superheated steam (up to 118 °C) [16] with high flow rates are along the eastern flank of the 5150 m high Apacheta volcano.

El Tatio

El Tatio is located 100 km E of Calama City at an altitude of 4300 m a.s.l. Several thermal springs, fumaroles, geysers and boiling and mud pools are present. Hydrogeological models [17, 18] indicate that meteoric waters infiltrate in recharge areas 15 km E from the field. The main hydrothermal reservoir is confined within the permeable Puripicar Formation and the

Salado Member. An important secondary aquifer occurs in the Tucle Dacite subunit that is capped by the impermeable Tatio Ignimbrite [17]. In figure 2 the simplified geological profile and circulation conceptual model are shown. The potential geothermal reservoir is hosted in Puripicar Formation and Salado Member, altough temperature close to 170°C was recorded in permeable levels hosted in the Grupo volcanic de Tucle [5].

In figure 3 a profile of the El Tatio Graben is shown. It crosses through the wells 1, 4, 9 and 7, from NW to SE. In the boreholes, three permeable levels were been detected, the permeability is, mainly, originated by tectonic fracturing or rapid cooling of the volcanic bodies. From top to the bottom the temperature ranges from 160/170°C to 260°C [19].

Irriputunco-Olca

The Irriputuncu-Olca field is characterized by the presence of the Irriputuncu and Olca Volcanos, located in the Chilean Altipiano at 4000-5000 m a.s.l. in the vicinity of the copper mine. Irriputuncu is an active dacitic stratovolcano, with fumaroles at the top crater and one acid-sulphate hot spring at the base of the volcano. Two slim boreloes (800 and 1430 m depth) evidenced a bottom hole temperature close to 150°C and 195°°C (at 3350 and 3000 m a.s.l., respectively) [20]. TEM-MT data suggests the presence of a potential deeper reservoir at about 220°C [20]. Olca is an andesitic volcano, the TEM-MT data evidences two conductive layers intercalated with resistive zones. Preliminary results suggest a potential of electric generation between 75 and 450 MWe [20].

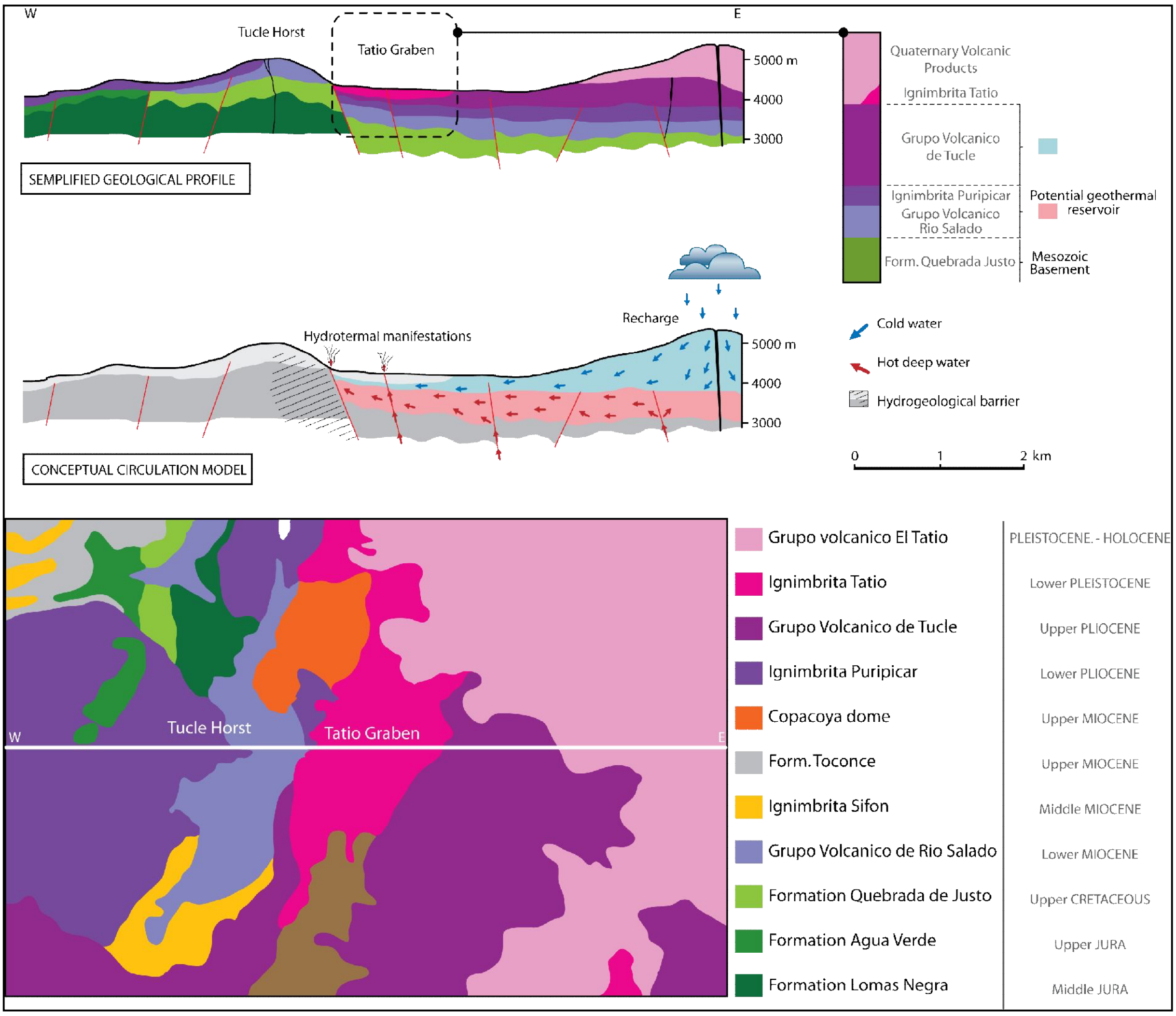

Figure 2: Semplified geological map of the El Tatio geothermal field, geological profile and circulation conceptual model. The dashed box represent the area in figure 4 (modified from, [1]).

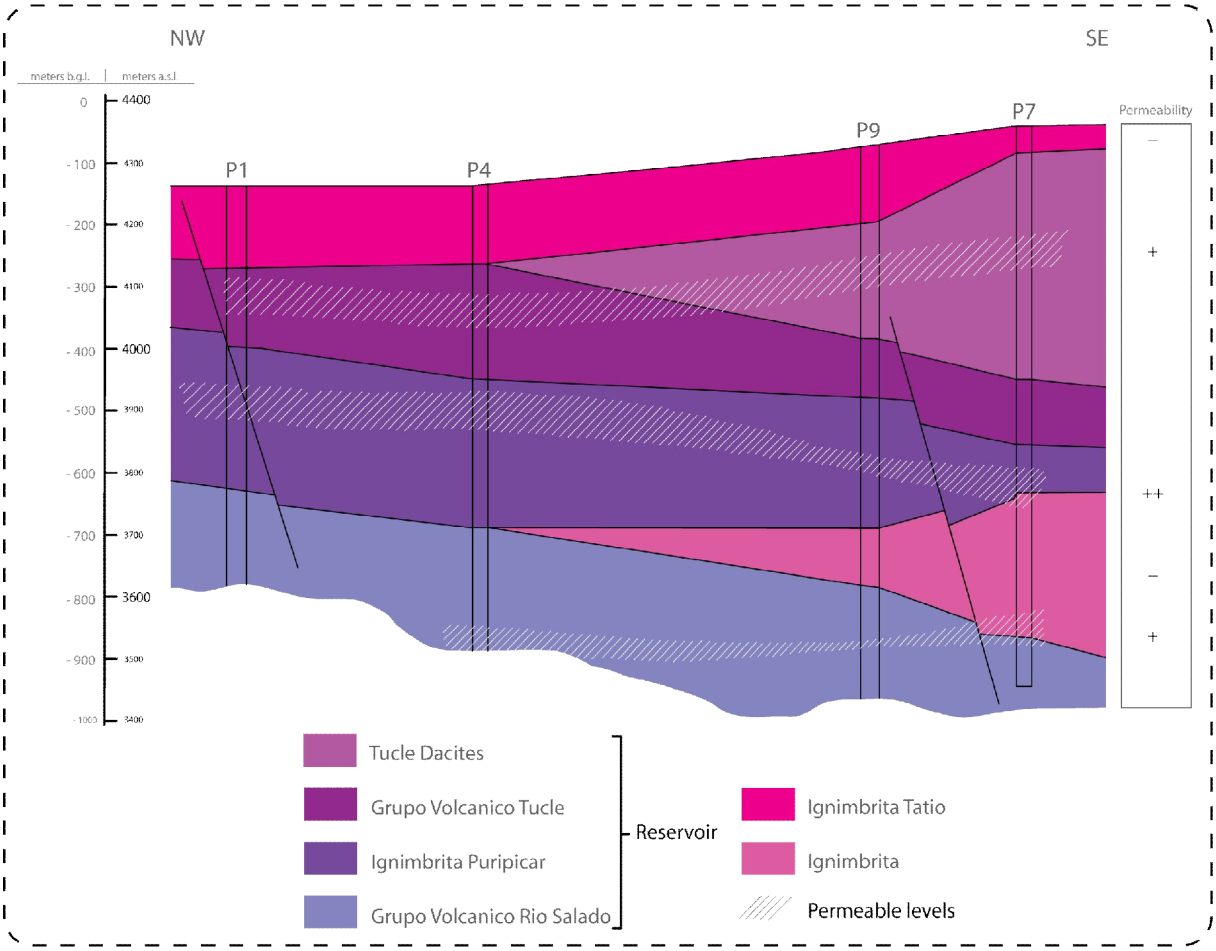

Figure 3: Geologicaal profile NW-SE, through the boreholes 1,4, 9 and 7. (modified from [1])

2.1 Geothermal exploration

Initial geothermal exploration in the CAVZ took place in late 1960s in response to increasing Chilean energy demands. At El Tatio a prefeasibility investigation, funded in 1967 by the Corporation for the Promotion of Development and the United Nations Development Program (CORFO/UNDP), in 1968–1980 was followed by geological, geophysical and geochemical surveys. Six 600 m deep exploration wells, drilled between 1969 and 1971, encountered temperatures up to 250 °C. In 1973 and 1974, seven production wells in the SE sector of El Tatio were projected to produce approximately 30 MW [21]. At Puchuldiza-, geological, geochemical and geophysical studies were performed by CORFO/UNDP (from 1968 to 1974) and by Japan International Cooperation Agency (JICA) (from 1978 to 1980) to evaluate geothermal potential. Temperatures up to 166 °C were measured in exploration wells at the depth of 900 m [22, 23].

In the Surire zone geological and geochemical [13, 24] investigations were carried out by CORFO between 1972 and 1979. Reservoir temperatures up to 230 °C were estimated by geothermometric calculations based on the water chemistry of the thermal discharges [24].

Geothermal exploration in the CAVZ was abandoned in 1982 because of both the remote location of the hydrothermal systems and economic factors. In response, after almost three decades, private and governmental companies (e.g., CORFO, Geotermica del Norte S.A., Geotermica del Tatio, and Empresa Nacional de Geotermia) have planned to conduct a new phase of geothermal exploration in the systems investigated in 1969–1982 as well as in other areas of northern Chile, i.e. Lirima, Torta de Tocorpuri, Apacheta and Irriputuncu-Olca, showing presence of thermal fluid discharges.

2. METHODOLOGY

In the selected potential geothermal fields, the minimum and maximum electric energy supply (E_{su}) has been evaluated considering an operation time of 8000 h/year. To evaluate the E_{su} it has been necessary the evaluation of both thermal (W_{th}) and electric power (W_e).

The W_{th}, extractable from the geothermal reservoir was computed using the following relation:

$$Wth = \mathrm{f} \times Q \times Cw \times (T - 298.15)$$

Where *Cw* (J/kgK) is the specific heat capacity of the fluids contained in the geothermal reservoir, and *T* is the reservoir temperature (K). The *f* is the factor 1000/3600, needed to convert *Q* from t/h to *kg/s*. The minimum reservoir temperature *T*-, and the maximum reservoir temperature, *T*+, have been used to computed the minimum (*W*-) and maximum (*W*+) thermal power, respectively.

The W_e was been estimated by the following equation:

$$We = Wth \times \eta$$

where the η represents the efficiency of the selected power plant. Conventional geothermal power plants have been chosen for temperature reservoir major than 170°C, whereas, binary plants (Organic Ranking Cycle) for temperature reservoir minor than 170°C. For conventional plants an η of 20% has been considered and for the binary plants an η *of* 16%, estimated by Di Pippo in 2007, [25] (fig. 4).

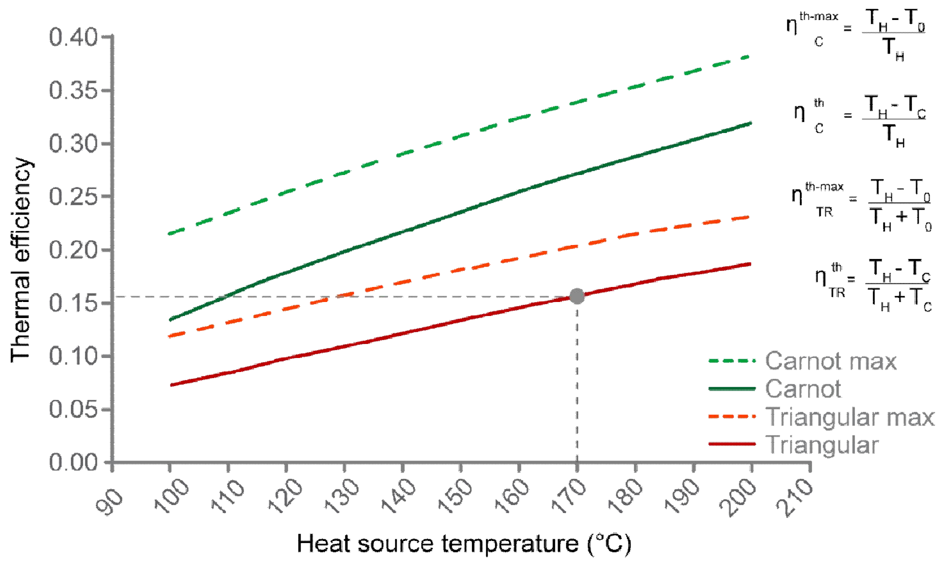

Figure 4: The thermal efficiencies of Carnot and Triangular cycles are compared (modified from [25]). In this report the η relative to the Triangular Cycle has been considered. This is a model more useful than the ideal Carnot Cycle because the latter, is applied only to reversible processes. It means that all heat transfer and work processes must be thermodynamically perfect. Moreover, there must be no heat loss and no increase in the entropy of the working fluid. Instead, the Triangular Cycle considers that the heating medium is not an isothermal source, but rather a fluid that cools as it transfers heat to the cycle working fluid [25].

The total E_{su} from the selected geothermal systems has been evaluated and a new energy scenario has been proposed for the northern Chile. Moreover the CO_2 emissions decrease was been evaluated considering the substitution, for the estimated E_{su}, of the crude oil with geothermal energy.

The relationship between CO_2 emissions and different energy resources use as coal, crude oil, natural gas and geothermal energy is shown in table 1.

	COAL	PETROLEUM	NATURAL GAS	GHEOTHERMAL ENERGY
CO_2 Emissions (g/kWh)	949	892	598	122
References	[26]	[26]	[26]	[27]

Table.1: CO_2 emissions for kWh by coal, petroleum, natural gas and geothermal energy [26, 27].

The hourly production rate Q is available for El Tatio geothermal field, only. Then for the others systems it was not possible to compute the W_{th}, and available data of W_e [16, 19, 20] have been taken into account for remaining evaluations.

3. Results

For the analysis, the geothermal systems of El Tatio, Surire, Puchuldiza, Irriputunco-Olca and Apacheta have been considered. A satisfactory dataset is available only for El Tatio geothermal field, whereas for the other systems partial data are present. The boreholes 7, 10 and 11 provide the main information for El Tatio, in terms of flow rate Q (t/h), minimum and maximum temperature and type of fluid (tab. 2). This geothermal system is water-dominated, the recorded Q ranges from 132 to 276 t/h, the temperatures from 170 to 260 °C and for Cw has been considered a value of 4.2 kJ/kgK. The minimum temperatures are recorded in Tucle Formation, whereas the highest temperatures in Puripicar and Rio Salado Formation.

The estimated minimum and maximum thermal powers (W_{th} -, W_{th} +) range from 20.2 to 40.4 MW_{th} and 34.2 to 71.4 MW_{th}, respectively. The electric power (W_e -, W_e +) has been estimated considering both conventional and binary geothermal power plants. For temperature up to 170 °C, an efficiency (η_{bp}) for geothermal binary plant of 0.16 has been considered. The estimated electric power ($W_{e\,-\,(bp)}$) ranges from 3.2 to 6.8 MWe. The maximum electric power (W_e+) has been computed considering the maximum recorded temperature, i.e. 260°C, and an efficiency (η_{cp}) of 0.2, relative to conventional geothermal plants. The values range from 6.8 to 14.3 MW_e. Therefore, the total electric power ($W_{e-(bp)}$) by binary plants use, is 16.4 MW_e; whereas by conventional plants, is 34.8 MW_e. The relative total energy supply ($E_{su\ (bp)}$ - E_{su}) is 131.5 and 278.2 GWh/y, for binary and conventional plants, respectively.

For the other geothermal systems i.e., Surire, Puchuldiza, Irriputuncu-Olca and Apacheta, the energy supply has been evaluated considering the electric power values provide by scientific literature [16, 19, 20]. The Database of Geothermal Resources in Latin America & the Caribbean [19] indicated for Surire and Puchuldiza, an electric power of 50-60 and 190 MW_e, respectively. Reyes et al. on 2011 [20] estimated the electric power for Irriputunco-Olca system in 75-450 MW_e, and Urzuà et al. on 2002 [16] evaluated the electric power for the Apacheta geothermal field in 400 MW_e. The computed energy supply (E_{su}) for the systems listed above, is reported in table 3. For the evaluation has been ever considering an operation time of 8000 h/y. The values range from 400 to 3600 GWh/y. The maximum estimated value of the total energy supply for the northern Chile is about 9078 GWh/h, considering the use of conventional geothermal plant. Whereas the minimum total energy supply is about 1132 GWh/y, considering for El Tatio an use of binary plants.

The total CO_2 emissions related to 9078 GWh/h are 1.1 Mton. The CO_2 emissions are about 8.1 Mton, considering the same energy amount, but by petroleum.

4. CRITICAL ANALYSIS

The Northern Chile has an huge geothermal potential, the performed evaluations for the El Tatio, Surire, Puchuldiza, Irriputunco-Olca and Apacheta geothermal fields show that the geothermal energy could provide about 9080 GWh/y, with a electric power of about 1135 MWe. Nowaday the SING (Northern Interconnected Power Grid) has an installed capacity of 4344 MWe and about 99% of which generated by imported fossil fuel (4300 MWe). The geothermal electric power could replace about the 26% of the SING installed capacity, decreasing the reliance on foreign fossil fuel providers. Moreover, the substitution of 1135 MWe from fossil fuel to geothermal energy, means a CO_2 emissions saving of about 7 Mtonn.

However the geothermal potential of the Northern Chile could be major than 1135MWe. Indeed geothermal resources characterized by medium temperature could be exploitated by geothermal binary plant as ORC or/and Kalina, increasing the development of the geothermal energy in unexplored areas and not considered in the past, also.

5. CONCLUSION AND RECOMMENDATIONS

Chile is rich in natural resources such as copper, timber, nitrates, precious metals and molybdenum. Even though Chile has an abundance of copper and mining resources, it has limited indigenous fossil fuels, indeed over 90% of the fossil fuels need to be imported.

Indeed, the SING (Northern Interconnected Power Grid) has an installed capacity of 4344 MWe and about 99% of which is generated by imported fossil fuel.

As suggest by the Global Energy Network Institute (GENI) in 2011, a strategic energy plan for Chile is necessary in order to ensure the transitions from traditional power plants to renewable energy power plants. This transitions are necessary both to reduce the amount of greenhouse gases into atmosphere and to take off the dependence of imported fossil fuels. The development of the geothermal energy can represent a useful tool for this purpose.

Then, in this paper a new evaluation of the Northern Chile geothermal potential has been performed, focusing on El Tatio, Surire, Puchuldiza, Orriputunco-Olca and Apacheta geothermal fields. Thermal, electric power and electric energy supply have been calculated, even though a satisfactory dataset is available only for El Tatio. The total estimated electric power for the northern Chile is about 1135 MWe and the energy supply 9080 GWh/y. This means that the 26% of the SING energy could be substitute from fossil fuel to geothermal energy, saving 7 Mtonn of CO_2. The geothermal energy development could be useful for mining and industry sectors, that represent the main energy user. As a final remark, an analysis of the field accessibility should be necessary, because the most part of the considered geothermal systems are remote sites.

WELL	Q (t/h)	f	Cw (J/kgk)	T- (°C)	T+ (°C)	K	W_{th} - (MW)	W_{th} + (MW)	η_{cp}	W_e - (MW)	W_e + (MW)	η_{bp}	$W_{e - (bp)}$ (MW)	OPERATION TIME (h/y)	E_{su} (GWh/y)	$E_{su - bp}$ (GWh/y)
7	276	0.28	0.0042	170	260	273.15	42.2	71.4	0.2	8.4	14.3	0.16	6.8	8000	114.3	54.0
10	132	0.28	0.0042	170	260	273.15	20.2	34.2	0.2	4	6.8	0.16	3.2	8000	54.6	25.8
11	264	0.28	0.0042	170	260	273.15	40.4	68.3	0.2	8.1	13.7	0.16	6.5	8000	109.3	51.7
References	[1]			[1]	[1]							[25]				
TOT										**20.5**	**34.8**		**16.4**		**278.2**	**131.5**

Tab. 2: Available data for El Tatio geothermal field and results of the evaluations.

GEOTHERMAL SYSTEM	A (km^2)	H (km)	Q (t/h)	T^- (°C)	T^+ (°C)	T_0 (°C)	RESERVOIR	W_e^- (MW_e)	W_e^+ (MW_e)	OPERATION TIME (h/y)	E_{su}^- (GWh/h)	E_{su}^+ (GWh/h)	References
EL TATIO	30	0.5	Tab.2	170	260	40	Liquid-Dominated	16.4	34.8	8000	131.5	278.2	[5]
SURIRE	45	/	/	110	234	40		50	60	8000	400	480	[19]
PUCHULDIZA	50	/	/	175	200	40		/	190	8000	/	1520	[19]
IRRIPUTUNCO (OLCA)	15	/	/	230	300	40		75	450	8000	600	3600	[20]
APACHETA	25	/	/	200	325	40	Vapor-Dominated	/	400	8000	/	3200	[16]
TOT								141	**1134.8**		1131.5	**9078.2**	
CO_2 Emissions (Mtonn)											0.14	**1.1**	

Tab. 3: Available data for Surire, Puchuldiza, Irriputunco-Olca and Apacheta geothermal fields and results.

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